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Annual Report

Covering the Period 1 January 1967 to 31 December 1967

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DETONATION CHARACTERISTICS OF LOW DENSITY GRANULAR MATERIALS

Prepared for:

DIRECTOR OF ENGINEERING SCIENCES
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
ATTN: SREP
WASHINGTON, D.C. 20333

CONTRACT AF 49(638)-1669

STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA



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ABSTRACT

This report summarizes work carried out during 1967 under Contract AF49(638)-1669 on detonation characteristics of low-density granular materials. The purpose of the research under this and preceding contracts is to clarify the processes during initiation to detonation in propellants and explosives. Toward this end studies have been made of (a) the mechanisms of initiation and propagation in low-density NH_4ClO_4 , (b) the properties of initiating shocks, (c) the loci of shocked states achieved in low-density granular aggregates, (d) hot spots in shocked granular NH_4ClO_4 and KCl, and (e) friction and jetting as possible causes of hot spots.

The main conclusions are that shocks greater than about 5 kbar are reactive in granular NH_4ClO_4 at a density of 1.0 g/cm³, that the reaction occurs from the time of shock entry and therefore is at least partially in the shock front, and that the likely sites of this shock-front reaction are hot spots which occur when the interstices collapse. These hot spots have been photographed at about 40 kbar.

0.1 μ sec was the shortest usable exposure time. A typical example of the hot spots produced in NH_4ClO_4 with the 40 to 50 kbar shock pressure induced is shown in Fig. 4. A similar picture of hot spots in a KCl bed is shown in Fig. 5.

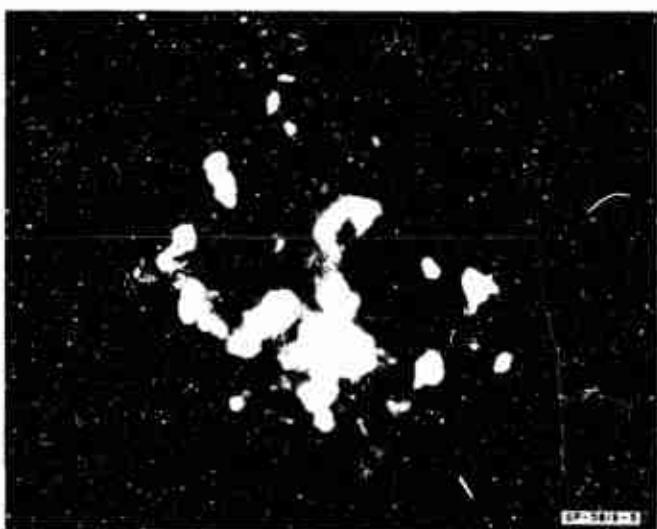


FIG. 4 IMAGE CONVERTER PICTURE OF HOT SPOTS IN AN AGGREGATE OF NH_4ClO_4 . The shock pressure was between 40 and 50 kilobars. The atmosphere was methane. The Beckman and Whitley image converter was operated at an exposure time of 0.1 μ sec with ASA 10,000 Polaroid film.

The light intensity and duration measurement was made through the same objective lens by using a slightly silvered mirror placed ahead of the fast-shuttering image converter tube. The light measurement was thus the total output over the entire crystal bed as a function of time as the shock wave traversed the depth of the bed. The time of the image converter exposure can be correlated with the photomultiplier record. For crystal beds approximately 3 mm deep, the light lasted about 2 μ sec in all cases. When the crystals were NH_4ClO_4 , the light output peak was two to three times that reached when the crystals were KCl. This observation does not in itself indicate a difference in reactivity between the materials, since the KCl crystals are not completely transparent and might be expected to

I INTRODUCTION

This report describes work carried out between 1 January 1967 and 31 December 1967 on Contract AF 49(638)-1669, "Detonation Characteristics of Low-Density Granular Materials." The purpose of the work is to develop a basic understanding of factors controlling the shock sensitivity of propellants and explosive materials.

Shock sensitivity is a fundamental property of propellants or explosives which often determines their vulnerability to unfavorable environments. Detailed analytical and experimental studies on the shock sensitivity of ammonium perchlorate (a component of many propellant mixtures and a low-powered insensitive explosive in its own right) have shown a number of initiation characteristics that apparently apply to granular explosives generally. Thus, studies on this material are of interest not only to illustrate the behavior of a representative propellant component but also to demonstrate the properties of high explosives. As a high explosive, ammonium perchlorate (AP) might be expected to be unusual because of its low power and insensitivity, but the latter characteristic actually is particularly favorable for shock initiation studies. The shocks necessary for initiation of low-density AP, which are above 15 kbar, are easier to control and measure than shocks below 3 kbar, which are adequate to initiate PETN with measurable delays.

Most of our investigations have thus far been carried out at densities of 1 g/cm³, that is, on pressings of high porosity. By working with this porosity it is possible to emphasize the effects of heterogeneity. The advantage of the combination of low density and insensitivity is demonstrated by the accessibility of low-pressure shocked states, which makes it possible to define a region of positive slope on the locus of shocked states in the p,v plane.

Last year our research was directed toward demonstrating that the shock front in a granular reactive material such as NH₄ClO₄ was quite different from a shock front in an inert material such as KCl even at shock pressures as low as 10 kbar.¹ Sound velocities of porous compacts

of these materials were used to assist in constructing a shock-velocity/particle-velocity plot, which demonstrated a pronounced difference between NH_4ClO_4 and KCl aggregates above a particle velocity of 0.5 mm/ μ sec (corresponding to about 10 kbar). The difference between the two materials was also quite obvious in the p,v plane. Measurements with a light gas gun were used to confirm previous determinations on porous NH_4ClO_4 made with an explosive shock-generating system. It remained to determine the compressibility of the KCl aggregate at about 40 kbar and to determine the Hugoniot of NH_4ClO_4 at crystal density.

Carrying on toward the general objective of this research, which is to clarify the shock initiation and transition-to-detonation processes, we have this year worked in three areas:

1. Confirmation and extension of the loci of shocked states for NH_4ClO_4 and KCl.
2. Experimental investigation of the nature of hot spots in granular materials.
3. Formulation of theories of hot-spot formation according to the mechanisms of friction and hydrodynamic jetting.

II SHOCK COMPRESSION EXPERIMENTS

In last year's annual report, detailed experimental evidence was presented to show that the shock compression curve for granular aggregates of AP was quite different from that for aggregates of KCl at porosity $m = v_o/v_c = 2$. Two points remained to be established: The Hugoniot for NH_4ClO_4 at crystal density needed to be established more definitely so that the material could be compared with AP granular aggregates and with other solid crystals. The state variables for KCl aggregates at $m = 2$ were needed for pressures in the neighborhood of 40 kbar so that a clear comparison with the NH_4ClO_4 aggregate could be made in this pressure region.

A. Hugoniot for Single Crystal Ammonium Perchlorate

Previously we have drawn the ammonium perchlorate crystal Hugoniot to match the known curve for KCl, using sound velocity measurements to

reinforce our confidence in the low part of the curve. It will be desirable, however, to have detailed information on the Hugoniot of NH_4ClO_4 crystals to establish directly the magnitude of the deviation of the shock compression curve for the aggregate.

A Hugoniot compression point for a single AP crystal has been established using the light gas gun technique. (The method was described in the 1966 annual report and details of the technique are given in Ref. 2.) The measurement was for a plane shock perpendicular to the broad face of the crystal, the direction in which the lattice dimension is 7.453 Å. Because of crystal shape, it is not feasible to measure the compression in other directions with presently obtainable crystals; however, the measurement made is sufficient for comparison of this Hugoniot with that of other crystals and with randomly arranged, porous AP.

A brass plate about a quarter-inch thick was accelerated in the light gas gun to 0.408 mm/ μ sec and allowed to impact on a brass plate of similar thickness in the target assembly. A shock at about 0.20 mm/ μ sec (corresponding to roughly 68 kbar) was thus formed in the stationary brass plate. An ammonium perchlorate crystal* 1.763 mm thick was mounted on the rear face of the plate with a quartz gage on its far surface to record arrival times and allow estimation of pressures.³ The double-fronted wave recorded is shown in Fig. 1. By using the wave velocities corresponding to the crystal transit times indicated by the two fronts in this trace it is possible to calculate the pressure and volume of the final shocked state in the AP crystal.² The resulting state point, $p = 21$ kbar and $v = 0.46 \text{ cm}^3/\text{g}$, is indicated on the plot in Fig. 2. It lies close to the KCl crystal Hugoniot.

The nature of the trace in Fig. 1 contains qualitative information about the shock in crystalline ammonium perchlorate which has not been reported before. First appearing on the trace is a low-amplitude ramp A

* The crystals were generously furnished by Dr. William R. McBride of the Naval Weapons Center, China Lake, California.

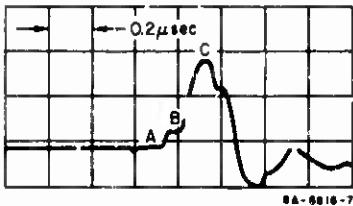


FIG. 1 QUARTZ GAGE TRACE OF SHOCK IN AMMONIUM PERCHLORATE CRYSTAL
Final pressure about 21 kilobars

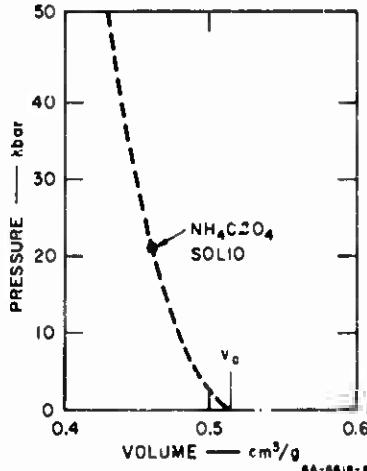


FIG. 2 SHOCK HUGONIOT FOR AMMONIUM PERCHLORATE CRYSTAL. The specific volume of the crystal is v_c .

whose cause has not been determined and which can probably be ignored in view of its small magnitude. The small negative signal at the beginning of the ramp is an electronic reaction produced by the particular pre-amplifier used. The second feature of the trace is a rapidly rising signal B traveling at $4.3 \text{ mm}/\mu\text{sec}$. The final pressure rise is traveling at $3.3 \text{ mm}/\mu\text{sec}$, and produces the final compression in the crystal. This double-fronted wave in ammonium perchlorate probably arises from a polymorphic transition. The height of the precursor B indicates that this phase change may take place as low as 5 kbar. Since the existence of the new phase in the solid crystal is somewhat peripheral to shock initiation of granular aggregates, we have not performed confirming experiments. However, the possibility of this phase will be of interest to those concerned with the effects of shock on solid ammonium perchlorate, and it may be an important consideration in the shock vulnerability of AP-containing propellants.

B. Shocked Porous KCl

In last year's annual report, measurements on aggregates of KCl at porosity $m = v_0/v_c = 2$ were reported in the pressure range below 20 kbar. Measurements were made with explosive shock-generating systems and with the light gas gun. It was apparent that the shock-compacted state of these aggregates lay close to the KCl crystal Hugoniot. Although it is thermodynamically impossible for them to lie exactly on the crystal curve, their position is very close to that called for by the compressible locking-solid model. Linde and Schmidt² report such dynamic results for porous aluminum samples ($m = 1.3$ to $m = 2.5$). Furthermore, samples recovered after shocking to pressure in the range from 5 to 60 kbar exhibited densities close to that of solid aluminum. Dynamic measurements also showed that the compacted volumes of porous graphite above a few kilobars were essentially those of the solid material at the same pressure. On the other hand, Russian data⁴ on porous KCl at higher pressures indicate that the shocked states of the aggregates occupy noticeably greater volumes than those of the solid crystal. The two sets of results are not in direct contradiction, since the pressures are quite different. But it is important for our purposes to know to what pressure the complete collapse of the KCl aggregate persists and to be able to define the nonreactive KCl curve over the region in which the specific volume of shocked NH_4ClO_4 aggregate is larger than crystal density.

Two experiments were conducted with an explosive shock-generating system using the techniques described at the Fourth Detonation Symposium.⁵ A pressure in the neighborhood of 40 kbar was obtained with an explosive shock system consisting of 19 mm of magnesium and 9 mm of Plexiglas on a P-80 plane wave generator. The aggregate beds were pressed from KCl particles with diameters of 13μ to a density of 1.0 g/cm^3 ($m \approx 2$). Seven samples were shocked in the first experiment and five in the second. The results of the two experiments were essentially in agreement, as shown by the open squares near 40 kbar in Fig. 3.

The conclusion from these experiments is that KCl aggregates at porosity $m = 2$ collapse essentially to the volume of compressed crystal

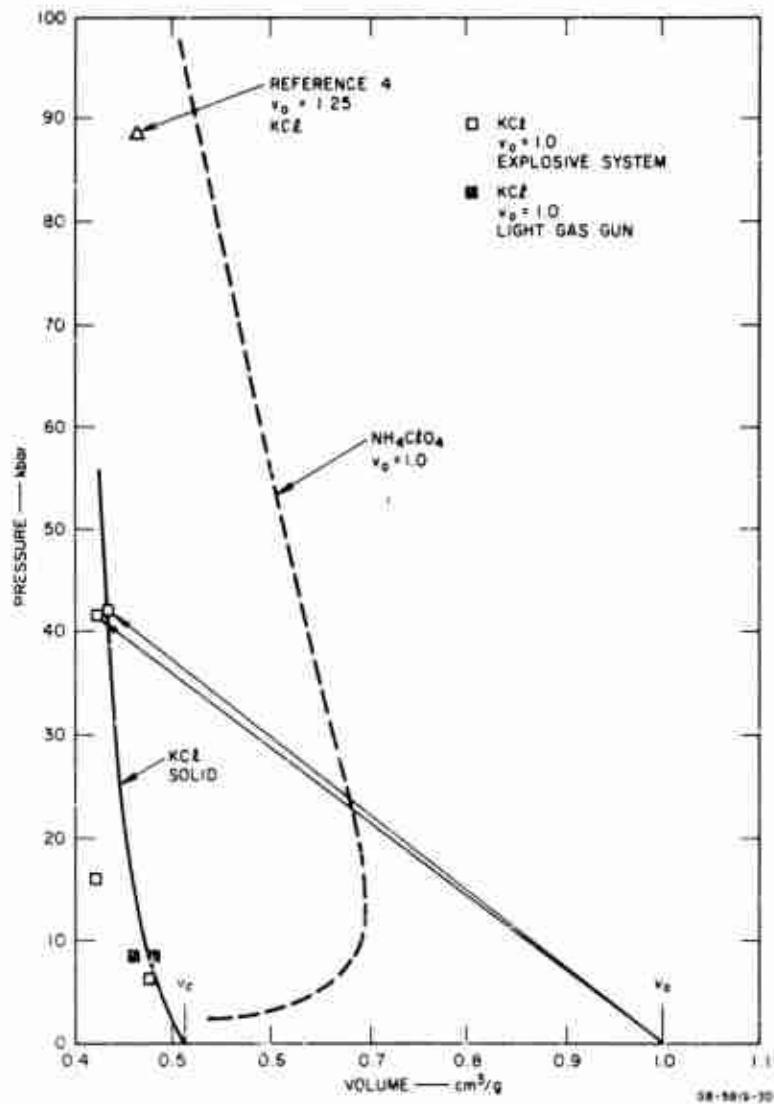


FIG. 3 SHOCK COMPRESSION OF POTASSIUM CHLORIDE AGGREGATES
AT POROSITY $m = 2$. New data are the squares at the points of arrows
originating at initial specific volume of the aggregates v_0 .

KCl at the same pressure. We must accept the data of Körner et al.⁴ indicating that at higher pressures the shocked states are noticeably different from those attained by the shocked crystal. Apparently this difference becomes noticeable somewhere between 43 and 89 kbar.

III HOT SPOTS IN SHOCKED GRANULAR MATERIALS--EXPERIMENTAL WORK

In our work on the shocked states of AP aggregates we have shown that the locus of shocked states is different in kind from the locus for KCl aggregates. These loci have been constructed on the basis of the entering shocks in the aggregates. Therefore we have concluded that a certain amount of chemical reaction occurs at the front of the shock in AP aggregates, and that this accounts for the different shock state loci. If such reaction is to occur at the shock front it will occur at the hottest regions there. Hot spots have been observed in detonating materials,⁶ in initiating shocks,⁷ and in shocks in inert materials.^{8,9} We have therefore undertaken a study of the characteristics of the hot spots, to establish the connection between these centers of early reaction in the shock wave and the displaced locus of shocked states in granular ammonium perchlorate.

We have successfully photographed hot spots in shocked granular materials with a Beckman and Whitley image-converter camera at very short exposure times. Beds of crystals 1 to 2 mm in size, both KCl and NH_4ClO_4 , were shocked by a calibrated system consisting of an explosive pellet and a Lucite attenuator. The Lucite was thoroughly blackened to eliminate light from the pellet and the bed was flooded with methane to avoid gas shock luminescence. Relative intensity and duration of the light generated by the crystals were recorded with a photomultiplier tube.

This exploratory phase of the study has covered two pressure ranges, the higher being somewhat above 100 kbar and the lower being approximately 40 to 50 kbar in the crystal bed. Precise statement of pressure in this coarse-grained, heterogeneous material is not possible using continuum hydrodynamic methods. Successful photographs of the hot spots were made at the high pressure range with exposures as short as 0.05 μsec . At the low pressure range, with less light produced in the shock process,

0.1 μ sec was the shortest usable exposure time. A typical example of the hot spots produced in NH_4ClO_4 with the 40 to 50 kbar shock pressure induced is shown in Fig. 4. A similar picture of hot spots in a KCl bed is shown in Fig. 5.

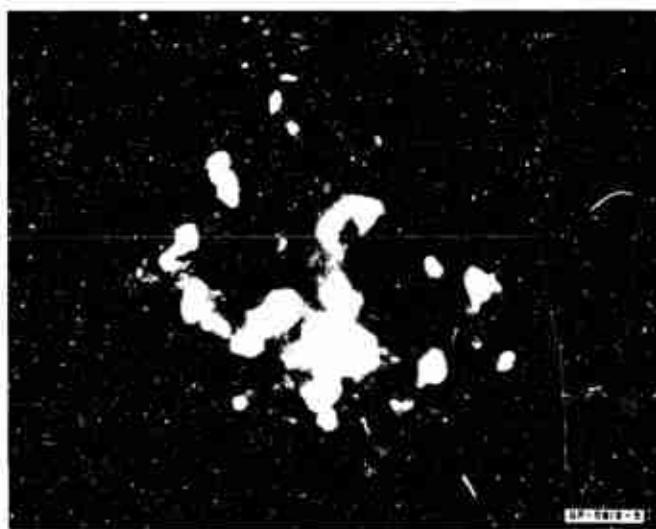


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attenuate and scatter light more than the NH_4ClO_4 crystals. However, since we have previously observed a dramatic difference in shock compression behavior for the two materials when they are in finely divided porous form, the increased light output in shocked NH_4ClO_4 crystals seems most likely to be another evidence of early reaction.



FIG. 5 IMAGE CONVERTER PICTURE OF HOT SPOTS IN POTASSIUM CHLORIDE AGGREGATE. Same conditions as for Fig. 4.

IV HOT SPOTS BY FRICTION OR JETTING

We conclude from our work on the loci of states achieved in NH_4ClO_4 and KCl aggregates that reaction occurs in the front of initiating shocks. Postulation of hot spots is required to reach reactive temperatures. Very hot localized regions have been observed in detonation fronts in granular explosives.^{6,7} In the preceding section of this report image converter pictures of hot localized regions were shown in shocked beds of NH_4ClO_4 and KCl granules when the shock was around 40 kbar. Presumably, cooler hot spots also exist at lower shock pressures, and it is hoped this can be demonstrated by photomultiplier measurements over a lower range of pressures.

In detonations, where the products can reasonably be presumed to act like gases, stagnation is a probable mechanism for hot spots.⁶ However, in initiating shocks it is not clear that collapse of the interstices produces gas until after local reaction occurs. It seems reasonable, therefore, that a process involving the solid material should be considered. The following account summarizes a treatment by William Band of local heating in shocked granular materials.¹⁰

Consider a shock front arriving at the free surface of a cavity in a granule (or between two granules). The shock reflects at the free surface, but continues on either side of the cavity.

The diagram in Fig. 6 gives an idealized geometry. If u is the particle velocity behind the shock, the velocity of the free surface in the state left behind by the reflected rarefaction is about $2u$. A relative motion therefore exists between the material A, as it proceeds to fill the cavity, and the material B at the sides. If a pressure is maintained by the shock across this interface, friction can dissipate some of the mechanical energy into heat.

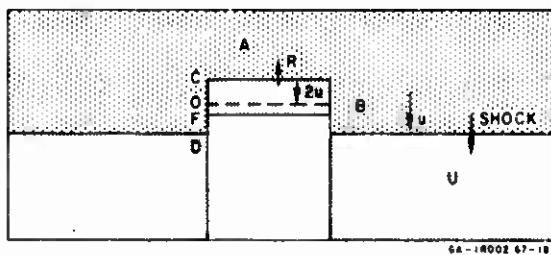


FIG. 6 IDEALIZED DIAGRAM OF THE ACTION OF A SHOCK ON A CAVITY IN A CRYSTAL OR IN AN INTERSTICE
Temperatures are calculated as the result of friction between material from the top of the cavity moving at twice the particle velocity $2u$ and material above the side walls moving at velocity u .

In many materials, solid rigidity does not vanish immediately but may persist for a time from 10 nsec to as long as 1 μ sec. After the onset of the shock pressure there will be a very short time τ during which it would be legitimate to think of the friction as sliding friction between two solid surfaces. During this short time, shear stresses comparable with the pressure p will do work by friction over the relative displacement of the two surfaces.

Actually, the shock velocity is usually considerably greater than $2u$, so the high-pressure slippage is limited to the region above the cavity. We approximate the area of effective contact $A = \pi sU\tau$ where s is the linear dimension of the cavity and U is the shock velocity. The distances of relative motion between the surfaces is $u\tau$. The work done by friction is thus

$$\Delta W_1 = \emptyset p A u \tau = \emptyset p s \tau^2 / \rho$$

where \emptyset is the coefficient of friction, the volume heated is $A\lambda$, λ is the thickness of the heated layer, and we assume this is determined by thermal diffusion during the time τ . Lambda is then given by $\lambda = \sqrt{\pi K \tau / \rho C}$ where K is the thermal conductivity and C is the specific heat. The maximum temperature rise from this source of heat is therefore

$$\Delta T_1 = \emptyset p u \tau / \rho C \lambda = \emptyset p u \sqrt{\tau} / \sqrt{\pi K C} \quad (1)$$

After a time $t > \tau$, the temperature drops by diffusion:

$$\Delta T_1(t) = \Delta T_1(\tau) \sqrt{\tau/t} \quad (1a)$$

Some modification of this statement is to be expected from the geometry of the cavity surface, but as an order of magnitude calculation, (1) and (1a) should give a good idea of expected heating. There is nothing in this result to account for the significant effects of cavity size that are observed experimentally.

As the shock envelops the cavity, the sideways-propagating relief waves develop and the cavity collapses from the sides. Material from the

boundary layer between A and B is thus caused to jet into the cavity and may strike the floor of the cavity before it has collapsed. If this impact occurs on previously unshocked material, the same sudden shear stresses can be initiated at the boundaries of the area struck by the hypervelocity jet. Another increase in temperature therefore occurs here, given by the same type of relation:

$$\Delta T_2 = \theta p' u' \sqrt{\tau} / \sqrt{\pi k \rho c} \quad (2)$$

where p' and u' refer to the shock induced in the floor of the cavity by the jet impact.

The ratio $p' u' / p u$ depends on the cavity size, and we shall develop a simple model for which this is true. We therefore accept the ratio

$$\beta = \theta p' u' / p u$$

as an effective conversion factor and write

$$\Delta T_2 = \beta p u \sqrt{\tau} / \sqrt{\pi k \rho c} \quad (2a)$$

Results are listed in Tables I through III for PETN, KCl, and NaCl. In using (2a) we are plagued with several unknown parameters, the "worst of which is the "coefficient of friction," or the ratio of the shear stress to the pressure during initial slipping. If θ is assumed as small as 0.01, $p' u' / p u$ no greater than 5, and $\tau = 10^{-8}$ sec, the temperature in PETN will come up to $\Delta T_2 = 900^\circ$.

The next problem is to consider the relation between β and the cavity size.

In these calculations we have assumed that:

- I. The rarefaction front travels a distance $OC = u\tau$ (Fig. 6) during the operation of the friction before it arrives at the back of the granule:

$$s_g > u\tau$$

TABLE I
LOCAL HEATING IN GRANULAR PETN^a

<u>p/10⁹ (dynes/cm²)</u>	<u>u/10⁴ (cm/sec)</u>	<u>(s_g/s_c)[*]</u>	<u>Δ T/10³β Deg.C</u>	<u>Δ T_j^b Deg.C</u>
1	0.4	2.74	0.32	12.9
2	0.75	2.06	1.21	45.0
3	1.1	1.69	2.66	89.0
4	1.45	1.53	4.67	170.0
5	1.8	1.43	7.25	260.0
6	2.1	1.38	10.1	353.0
7	2.35	1.35	13.3	442.0
8	2.6	1.33	16.7	541.0
9	2.85	1.31	20.7	650.0
10	3.1	1.29	25.0	769.0
12	3.5	1.27	33.8	980.0
14	3.9	1.26	44.0	1220.0
16	4.15	1.26	53.5	1380.0
18	4.4	1.26	63.8	1550.0
20	4.65	1.26	74.9	1730.0

a. $\rho = 1.8 \text{ g cm}^{-3}$, $K = 2.5 \times 10^4 \text{ g cm sec}^{-3} \text{ deg}^{-1}$, $C = 1.1 \times 10^7 \text{ erg g}^{-1} \text{ deg}^{-1}$,
 $\tau = 10^{-8} \text{ sec}$, $1/\sqrt{\pi K C} = 8.05 \times 10^{-7}$, $\lambda = \sqrt{\pi \tau K / \rho C} = 6.3 \times 10^{-6}$

b. This column gives the temperatures expected if we have only the heat obtained by "stagnation" of the jet at speeds about $4u$ --
 $\Delta T_j = \frac{1}{2}(4u)^2/C$.

TABLE II
LOCAL HEATING IN GRANULAR KCl^a

$p/10^9$ (dynes/cm ²)	$u/10^4$ (cm/sec)	$(s_g/s_c)^*$	$\Delta T/10^3\beta$ Deg.C	$\Delta T_j/10^3$ ^b Deg.C
10	1.5	2.5	2.83	0.264
20	3.0	1.75	11.34	1.06
30	5.8	1.33	32.9	3.95
40	6.8	1.31	51.4	5.43
60	8.8	1.26	99.8	9.10
80	10.7	1.24	162.0	13.45
100	12.9	1.20	244.0	19.55

a. $\rho = 1.984 \text{ g/cm}^3$, $K = 6.7 \times 10^5 \text{ g cm sec}^{-3} \text{ deg}^{-1}$, $C = 0.68 \times 10^7 \text{ erg deg}^{-1} \text{ g}^{-1}$,
 $\tau = 10^{-8} \text{ sec}$, $1/\sqrt{\pi K \rho C} = 1.89 \times 10^{-7}$, $\lambda = \sqrt{\pi \tau K}/\rho C = 1.25 \times 10^{-5}$

b. This column gives the rise in temperature expected if only the heat obtainable from the cavity-jet at speed $4u$ is included.

TABLE III
LOCAL HEATING IN GRANULAR NaCl^a

$p/10^9$ (dynes/cm ²)	$u/10^4$ (cm/sec)	$(s_g/s_c)^*$	$\Delta T/10^3 \beta$ Deg.C	ΔT_j Deg.C
2	0.3	6.2	0.126	8.4
4	0.55	4.1	0.462	28.0
6	0.80	3.2	1.080	60.0
8	1.05	2.7	1.760	103.0
10	1.13	2.8	2.370	120.0
12	1.55	2.2	3.910	224.0
14	1.80	2.0	5.290	303.0
16	2.00	1.9	6.820	374.0
18	2.25	1.8	8.510	473.0
20	2.45	1.8	10.290	560.0
30	3.60	1.5	22.700	1210.0

a. $\rho = 2.165 \text{ g/cm}^3$, $K = 4.0 \times 10^5 \text{ g cm sec}^{-3} \text{ deg}^{-1}$, $C = 0.54 \times 10^7 \text{ erg g}^{-1} \text{ deg}^{-1}$,
 $\tau = 10^{-8} \text{ sec}$, $1/\sqrt{\pi K \rho C} = 2.1 \times 10^{-7}$, $\lambda = \sqrt{\pi K}/\rho C = 2.63 \times 10^{-5}$

b. This column gives the temperature rise expected if only the heat obtained by "stagnation" of the jet at speed about $4u$ is included.

2. The reflected shock from the bottom of the cavity does not limit the depth of the low-pressure, high particle-velocity material to be less than the distance $u\tau$:

$$s_c(1 + U/2u) > u\tau$$

If either or both of these conditions are violated, the correct formulas become the following:

If $s_g < u\tau$, friction operates for only the time $\tau' = s_g/u$ and the work done is only

$$\Delta W'_1 = \emptyset p A s_g$$

while the temperature increase is

$$\Delta T'_1 = \emptyset p s_g / \lambda' \rho c \quad (1b)$$

where

$$\lambda' = \sqrt{\pi K \tau' / \rho c}$$

or finally

$$\Delta T'_1 = \emptyset p u s_g / \sqrt{\pi K \rho c} \quad (1c)$$

If $s_c < u\tau/(1 + U/2u) < s_g$, heating is reduced by the factor s_c/s_g and the correct relation is

$$\Delta T''_1 = \emptyset p s_c \sqrt{u/s_g} / \sqrt{\pi K \rho c} \quad (1d)$$

Similar modifications would be expected in the expressions for ΔT_2 . If $s_g > u\tau$ while $s_c < u\tau(1 + U/2u)$, we must return to (1a) and reduce that by the factor $s_c(1 + U/2u)/u\tau$:

$$\Delta T'''_1 = \emptyset p s_c (1 + U/2u) / \sqrt{\pi K \rho c} \quad (1e)$$

These results suggest that experiments should be designed to find the value of τ . For a fixed porosity ratio (s_c/s_g fixed) find the maximum grain size beyond which the temperature no longer appears to increase with s_g :

$$\tau = s_{g\max}/u$$

Then for a fixed $s_g < s_{g\max}$ look for a maximum porosity or cavity size beyond which the temperature no longer increases with s_c :

$$\tau = (1 + U/2u)s_{c\max}/u$$

If the cavity size s_c is less than $u\tau$, there is not sufficient time for the material to lose its solid rigidity, but if $s_c > u\tau$, then the solid behaves hydrodynamically, and material can jet into the cavity.

Consider a cylindrical cavity in which the shock has been reflected from the top (Fig. 7). This surface is moving down at speed $2u$, and the sides are moving in at speed u . The angle of the interface is $\theta = \tan^{-1} \frac{1}{2}$ (more exactly it is greater than this, because the sides are inclined to the axis of the cylinder because of the finite speed of the shock). To reduce the point of contact, O, to rest, we impress a velocity $\sqrt{5}u$ along the line of contact. The flow picture is shown in Fig. 8. Bernoulli's equation for uniform pressure (in the cavity) evidently requires the jet to be a composite of two parts having different speeds v and $2u$. We write α for the fraction of the material arriving from the top of the cavity that goes into the jet, and β for the corresponding fraction from the sides. Conservation of momentum leads to the results

$$\begin{aligned}\alpha &= \frac{1}{2}(1 - 1/\sqrt{5}) \\ &\approx 0.277.\end{aligned}\quad \begin{aligned}\beta &= \frac{1}{2}(1 - 2/\sqrt{5}) \\ &\approx 0.051.\end{aligned}$$

We now have to picture a cone of materials (shown in Fig. 9) with a vertex at rest in the laboratory coordinates as the cavity collapses. The inside of the cone is flowing at the speed $u + \sqrt{5}u$, and the outer part of the cone at the speed $2u + \sqrt{5}u$. To conserve momentum it turns

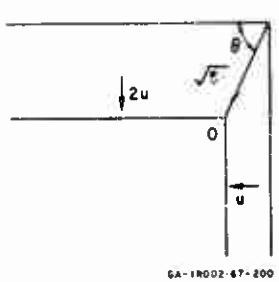


FIG. 7 CONDITIONS AT THE CORNERS
OF A CYLINDRICAL CAVITY
UNDER THE ACTION OF A
SHOCK WITH PARTICLE
VELOCITY u NORMAL TO THE
TOP OF THE CAVITY

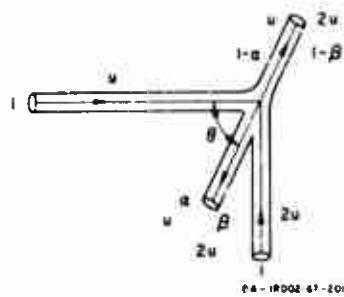


FIG. 8 JETTING AT THE
CORNERS OF A
CYLINDRICAL CAVITY

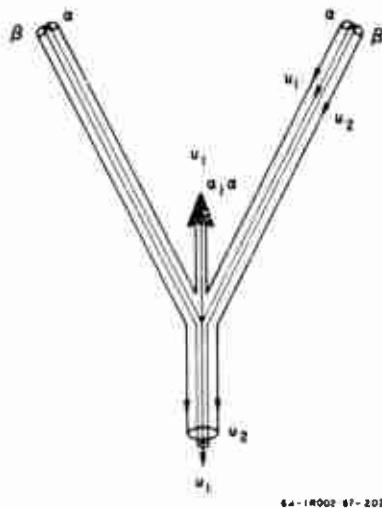


FIG. 9 INTERACTION OF JETS IN
A CYLINDRICAL CAVITY

out that, for the present geometry, the internal jet forms entirely from the inner layer, while the down-jet is composite: all the outer layer goes down and a core from the inside of the cone also goes down. Conservation of momentum leads to the result that the fraction of the inner layer jetting up is

$$\alpha_j = (1 - \sin\theta) (\frac{1}{2} + \beta u_2 / 2\alpha u_1)$$

where $u_1 = u(1 + \sqrt{5})$, $u_2 = u(2 + \sqrt{5})$. Numerically this turns out to be $\alpha_j = 0.0675$.

The net result is, then, that a fraction $\alpha \times \alpha_j = 0.019$ of the material in the top of the cavity jets back up, while $(1 - \alpha_j)\alpha = 23$ of the material from the top and 0.054 of the material in the sides jets down in a composite motion--the material from the sides having a speed 4.24 u and that from the top (in the core of the jet) only a speed 3.24 u. Assuming that this tidy, streamline picture can hold steady, we can imagine the head of the jet punching into the bottom of the cavity and causing a ring-shaped hot spot by the same mechanism already postulated for the top of the cavity. Both the pressure and the particle velocity induced in the solid would in first approximation be about double those in the original shock, so a rough estimate of $p'u'/pu$ is a factor of 4. It seems more realistic to suppose that the composite nature of the flow both in the cone and in the jets would induce turbulent degeneration of energy, and that the jet would therefore give a much smaller punch to the base of the cavity than estimated above.

In spite of the crudeness of the model and the assumptions that are necessary, the relationships between grain size and cavity size might give an insight into the consistency of the model. The ratio

$$s_{gmax}/s_{cmax} = 1 + U/2u$$

should be amenable to experimental check. Even though the absolute values of the area of friction may be wrong, the relative effects of grain and pore size should be as indicated.

VI PUBLICATIONS

During 1967 the following research note was published:

Reese, B.O., J.H. Blackburn, L.B. Seely, and Marjorie W. Evans,
"Longitudinal Sound Velocities of Granular Compacts of Ammonium Perchlorate
and Potassium Chloride," Combustion and Flame 11, 262-264 (1967).

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10. Band, W., "Local Heating in Shocked Granular Materials," Poulter Laboratory Internal Report 002-67, Stanford Research Institute, July 7, 1966.

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13. ABSTRACT

This report summarizes work carried out during 1967 under Contract AF49(638)-1669 on detonation characteristics of low-density granular materials. The purpose of the research under this and preceding contracts is to clarify the processes during initiation to detonation in propellants and explosives. Toward this end studies have been made of (a) the mechanisms of initiation and propagation in low-density NH₄ClO₄, (b) the properties of initiating shocks, (c) the loci of shocked states achieved in low-density granular aggregates, (d) hot spots in shocked granular NH₄ClO₄ and KCl, and (2) friction and jetting as possible causes of hot spots.

The main conclusions are that shocks greater than about 5 kbar are reactive in granular NH₄ClO₄ at a density of 1.0 g/cm³, that the reaction occurs from the time of shock entry and therefore is at least partially in the shock front, and that the likely sites of this shock-front reaction are hot spots which occur when the interstices collapse. These hot spots have been photographed at about 40 kbar.

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	ROLE	WT	ROLE	WT	ROLE	WT
Ammonium Perchlorate Detonation						
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Potassium Chloride Hugoniots						
Reaction in Initiating Shocks						
Reactive Shocks						
Sensitivity of Granular Explosives						
Shock Initiation of Granular Explosives						
Shock-to-Detonation Transition						
Hot Spots in Shocked Granular Compacts						
Friction Hot Spots						
Jetting and Hot Spots						

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